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5

Transient Memories

Conditioning Research Versus Memory Research

This chapter marks a transition from research focused on animal conditioning to research focused on human memory. The critical distinction is not so much the species of the subject as it is the methodology used—the conditioning experiment versus the memory experiment. The typical conditioning experiment involves a rather complex situation from the point of view of the organism. The organism is placed in a novel environment and is given some experiences that typically include strong manipulations of motivation. The experimenter is interested in the behavior that arises as a function of these experiences and motivational manipulations.

Figure 5.1 illustrates one way to conceive of what is happening in a conditioning experiment. The organism explicitly or implicitly has to figure out the structure of the environment, including reinforcement contingencies, from its experiences. The process by which it does so is sometimes called *induction*. The input to this process is its experience, possibly combined with biological predispositions and, in the case of humans, with some instructions. The result of this process is some knowledge of the environment, and this knowledge is deposited in memory. A process called *motivation* in Figure 5.1 then converts this knowledge into behavior. Figure 5.1 illustrates that this process of motivation is also affected by the organism's current goals. Memory is just one part of a larger system that is involved in a conditioning experiment; memory experiments try to focus on that one part.

Figure 5.1 also embodies the important discovery that learning processes are separate from motivational processes. Chapters 1 and 4 reviewed the evidence that motivation does not influence what is learned but how organisms display this learning. For instance, Tolman's rats learned about mazes in the absence of reinforcement, but displayed that knowledge only when food was put in the goal box. Thus, Figure 5.1 illustrates that motivation does not control what goes into memory, but rather how memory maps onto behavior.

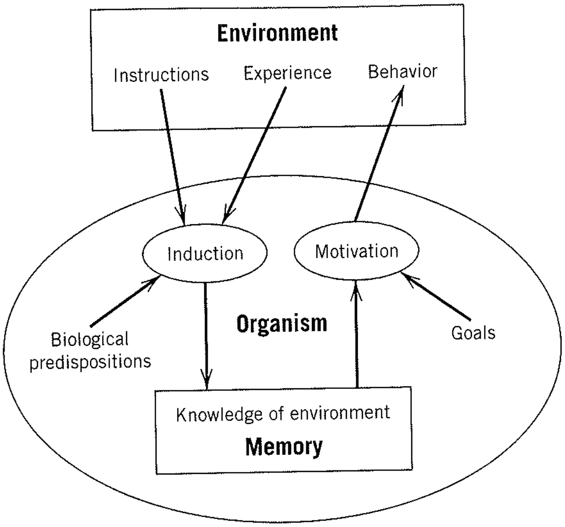

FIGURE 5.1 A conception of systems in a conditioning experiment.

Figure 5.1 is a rational reconstruction of the factors that must be involved in a conditioning experiment. It is not meant to imply that there is always an induction stage, a memory stage, and a motivation stage. For instance, in *Aplysia* (Chapter 2) learning involved directly associating sensory neurons to motor neurons. This learning process implicitly induced the relationship between the CS and the US, resulted in a memory stored at the synapse, and produced an adaptive reflex, but there were no separate induction, memory, and motivation stages. As noted throughout this book, organisms can behave as if they went through a rational process without really doing so. The higher the organism is on the phylogenetic scale, the more likely that such rational processes actually occur at least in some cases. However, even in humans there is undoubtedly simpler "as if" learning as well.

A conditioning experiment requires that the organism induce the contingency, remember it, and use this knowledge to achieve its goals.

Animal Research Versus Human Research

With this picture in mind, let us reflect again on the relative advantages of animal versus human experimentation, a topic mentioned in Chapter 1. Because of the greater complexity of human behavior, it is hard to study the full system shown in Figure 5.1 in one experiment, whereas a prototypical experiment with a rat in a Skinner box taps all aspects of the system. Animals are therefore often more suited for the study of the complete system. Animals are also often more suited for the study of a single aspect of the system as well because there are fewer ethical constraints regarding their treatment. Many experiments on the motivation and physiology of learning involve extreme manipulations that can only be done with animals.

Humans often offer advantages, however, because they can be more carefully directed through instructions and experimenters can count on their social cooperativeness to obtain appropriate information. The advantage of human subjects is strongest in the behavioral study of the memory system. In the typical conditioning experiment, the memory system is only indirectly connected to the environment. The induction phase intervenes between the input from the environment and the memory system. The induction system figures out what goes with what and hence what should be stored in memory. Humans can be instructed as to what goes with what, and so researchers can effectively bypass the induction phase and study memory directly. Whereas a rat must figure out that pressing a lever causes food to be delivered, a human subject can simply be told. Because it is so easy to inform humans about what they should remember, experimenters typically have human subjects learn an amount of information that would be almost intractable in a conditioning experiment. A simple human memory experiment might require subjects to learn 20 stimulus–response paired associations, such as dog–6, where they must respond with the second term when shown the first. Twenty such pairs are a herculean number of stimulus–response associations to train in a conditioning experiment. With human subjects, researchers can focus on the storage of information in memory and not on how the organism figures out what should be stored in memory.

Just as induction causes difficulty on the input side in a conditioning experiment, motivational processes on the output side also create difficulty in making inferences about memory. With humans, experimenters do not usually have to worry about setting up complex contingencies to get the subjects to show what they have learned; the experimenters can simply ask and rely on social cooperativeness.

These experimental advantages have made humans the subjects of choice in behavioral studies of memory. These studies have yielded a great deal of knowledge, which is explored over the next four chapters. Researchers have also set up experimental paradigms to tap similar issues about memory in lower animals and have found that animal memory often appears to behave similarly to human memory. This comparative research is important both because it tells us about other animals and because lower organisms can provide an understanding of the physiological basis of memory.

Research on human memory has another advantage: it is more obviously relevant to us. Subsequent chapters frequently explore the implications of research for our own need to learn and remember information. This memory research is nowhere more relevant than in education. The typical memory experiment is often a miniature of the learning processes involved in mastery of a subject domain (such as the one you are studying in this text). The last chapter of this book is devoted to developing the implications of research on learning and memory for education.

This chapter is concerned with transient memory, in contrast to the next three chapters which will be concerned with more permanent memory. Our system has numerous ways of temporarily holding information for further processing. These transient memories behave like a television screen. They hold information in a highly accessible form so that we can readily process it. However, once the information disappears, there is no record of what was once there unless it has been stored in some more permanent memory. In the television screen analogy, if one is not recording the program, one will not be able to recreate the contents of the screen. Many of these transient memories are quite sensory in character, and we will begin our discussion with storage of information in the systems that do processing of the sensory signals we receive from the environment.

Research on human memory focuses on a subset of the larger system that is involved in research on conditioning.

Sensory Memory

How does information from the outside world get registered in some permanent memory? Perceptual systems, like our auditory and visual system, convert sensory energy arriving at our sensors (eyes, ears, etc.) into perceptual representations. This perceptual information must be held in various sensory stores long enough so that we can identify what is being sensed and create a permanent representation of it. Much research has been devoted to the properties of the temporary stores that exist to hold visual and auditory information.

Visual Sensory Memory

One of the temporary memories is **visual sensory memory**, which holds information perceived by the visual system. Let's consider one line of experiments that has been used to study visual sensory memory. Take a brief glance at Figure 5.2, turn your eyes away, and try to recall what letters were there. Most people, if they have just one brief look (less than 1 sec), report that they are able to recall only four or five letters. This procedure seems to tell us about the capacity of visual sensory memory—that it can hold about four or five things. These infor-

X	M	R	J
C	N	K	P
V	F	L	B

FIGURE 5.2 Type of visual display used in visual report procedures.

mal observations have been confirmed by more careful laboratory studies in which subjects were given a very brief (e.g., 50 msec) exposure to an array of letters such as that shown in Figure 5.2. Such results might lead to the conclusion that only a few items can be stored in visual sensory memory.

Many subjects, however, indicated that they felt they actually saw more than the few letters they reported, but that the other letters faded before they could report them. Perhaps you have also had this experience. Sperling (1960) conducted a study that confirmed what the subjects were saying. As in the other experiments, he presented the visual array for a short period (50 msec). Rather than ask the subjects to report the whole visual array, he asked them to report one row from the array. Immediately after the array was removed, Sperling presented his subjects with a high tone, a middle tone, or a low tone. If the tone was high, subjects were supposed to report the top row; a middle tone corresponded to the middle row; and a low tone corresponded to the bottom row. This procedure is called the *partial report procedure,* in contrast to the whole report procedure, in which subjects must report everything. Sperling found that the subjects were able to recall a little over three of the four items that appeared in a row.[1]

Sperling concluded that immediately after the removal of the visual stimulus, the subjects' visual memories contained all the items in the array but that the items rapidly faded from that memory. He studied the time course of the decay by delaying presentation of the tone after removal of the array. Figure 5.3 shows how the number of letters that the subject could report decayed as the tone was delayed up to 1 sec: The number quickly dropped off. This result indicates that information in the visual sensory memory has a very short life. Probably much of what the subjects were able to recall after 1 sec reflected what they had identified in that second before they knew which row they would be asked to report.

Neisser (1967) called this short visual memory **iconic memory** and argued that it was critical in allowing us to recognize stimuli that are presented for only a brief duration. People need some system to hold the information until it is encoded into a more permanent form. **Encoding** information involves creating some long-term memory record for it.

Iconic memory appears to be sensory in character and may even reflect activation of the neural systems responsible for early visual processing. Sakitt (1976) argued that the icon is predominantly located in the photoreceptors of the retina. She showed that many of the timing and sensitivity properties of the iconic image mirror those of the rods, which are the photoreceptors in the eye responsible for night vision. According to this analysis, the icon is very much like the afterimage of a bright light at night. However, there has to be more to icons than afterimages because iconic images are obtained even when there are no rod-based afterimages (Coltheart, 1983).

[1] That their reports were not always perfect probably reflected difficulties in executing the reporting and the fact that some of that row might have faded before it could be reported.

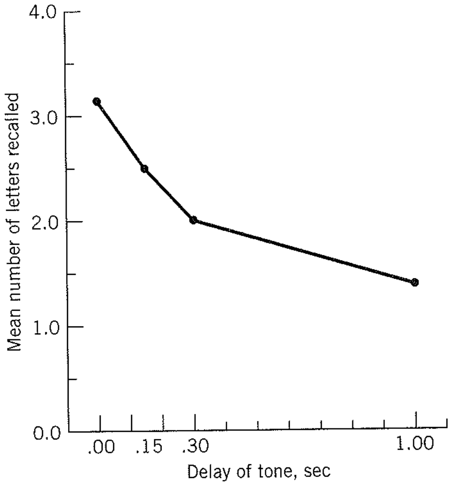

FIGURE 5.3 Results from Sperling's partial report procedure. As delay of signal is increased, number of items reported decreases.

Haber (1983) questioned the relevance of the icon for normal visual perception because humans do not usually perceive the world in such brief flashes; he argued that the icon would only be useful to reading in a lightning storm. Coltheart (1983) in a reply to Haber's criticism, noted that most of the information in normal processing is obtained within the first 50-ms. of fixation (moving our eyes to look at an object). Thus, it may not matter that there was only a 50-ms. flash in Sperling's experiment.

The evidence is quite persuasive that visual information exists in the system at many levels after we see something. A great deal of information is maintained in such a form but only briefly. However, there is not agreement as to the forms in which this information is maintained or how this information is used in higher-level cognition.

Sensory information is maintained in the visual system for brief periods of time.

Auditory Sensory Memory

Auditory information appears to be held in sensory memories just as visual information is temporarily stored in sensory memories. Early demonstrations of an **auditory sensory memory** were performed by Moray, Bates, and Barnett (1965) and Darwin, Turvey, and Crowder (1972). Darwin et al. presented subjects with simultaneous recordings of three lists of three items over two headphones. The items were letters and numbers; thus, one list might be 4 L 6. By stereophonic mixing of the signals from the two headphones, it appeared that one list was coming from the subject's left, another list from the subject's right, and a third from directly above the subject. As in the visual report procedures, subjects were not able to report all nine items (3 lists × 3 items) when asked to recall everything. However, the researchers also used a partial report condition similar to that used by Sperling. They asked the subjects to report just one of the three lists. They cued subjects as to which list to report by presenting a visual indicator on the right, middle, or left of a screen.

Subjects were able to report a higher percentage of the target set when they were cued than when they were told to recall the total list. Like Sperling, Darwin et al. interpreted this to mean that there were items in an auditory buffer that could not be recalled in the whole report procedure because they had faded from memory before the subject was able to report them. In the partial report procedure, subjects had to report fewer items and so got to reporting the critical items sooner. Darwin et al. also showed that the amount that could be reported in the partial report procedure decreased as the delay between the end of the lists and the cue increased. After 4 sec there was very little advantage for the partial report procedure. As in the case of iconic memory, this result indicated that items were decaying and that subjects were only able to remember something from the critical list if they encoded it before it had faded.

Neisser called the auditory sensory memory that held these items **echoic memory**. As in the case of iconic memory, he argued that people need some memory to hold the sensory experience so that it can be analyzed and encoded into a more permanent form.

Glucksberg and Cowan (1970) conducted a rather different experiment, which resulted in a similar estimate of the duration of the echoic store. They presented subjects with two spoken messages, one in each ear, and they required subjects to repeat the message that was being said in one ear. This task, called a *shadowing task*, is very demanding, and subjects typically remember nothing of what is said in the other ear. From time to time, the experimenters said a digit to the ear that was not being shadowed. They stopped the subjects and asked whether a digit had occurred. They found that if they asked subjects right after the digit, subjects could still detect it with some success. This performance dropped off dramatically over the first 2 sec, and after 5 sec the subjects showed no ability to detect the digit. The researchers concluded that in less than 5 sec echoic memory was completely lost for the unattended digit.

Conrad (1960) and Crowder and Morton (1969) showed not only that information decays from echoic memory with the passage of time but also that additional auditory information can interfere with it. Crowder and Morton presented the word *zero* just before asking subjects to recall a list of digits. Subjects were told to ignore the last *zero* and to recall the preceding digits. This final digit seriously impaired memory for the list. This phenomenon is called the *suffix effect* because an irrelevant suffix has been shown to impair memory. Impairment occurs because the *zero* enters auditory memory and interferes with the target list.

The interference associated with the suffix effect seems to be verbal in character. Crowder and Morton found that if they used a buzzer rather than a word as the suffix, there was no interference. Similarly, Ayres, Jonides, Reitman, Egan, and Howard (1979) found more interference with speech syllables as suffixes than with musical sounds. Thus, auditory memory appears to have a speechlike character. It appears that what is critical is whether the subjects think the sound is produced by humans. Neath, Surprenant, and Crowder (1993) found that a "baa" sound produced a suffix effect if subjects were told it was produced by a human but not if they were told it was produced by a sheep.

Oral or spoken information is maintained in the auditory system for brief periods of time.

Conclusions about Sensory Memory

Sensory memory is capable of storing more or less complete records of what has been encountered for brief periods of time, during which people can note relationships among the elements and encode the elements in a more permanent memory. If the information in sensory memory is not encoded in the brief time before it decays, it is lost. What subjects encode depends on what they are paying attention to. Typically, the environment offers much more information at one time than we can attend to and encode. Therefore, much of what enters our sensory system results in no permanent record. Similarly, instrumental conditioning research (see the discussion of dimensional learning in Chapter 3) has shown that animals often do not initially attend to certain aspects of the stimuli presented to them. Presumably, nonhumans are also overwhelmed by the richness of the stimuli they experience and can only pay attention to certain things.

Although the auditory and visual systems are perhaps the most important, they are not the only sensory systems that display transient memories for information. If someone steps on your foot, your tactile system remembers for a while which foot was stepped on. Athletes report motor memory for the recent performance of a skill. Information, as it is processed by many of our sensory systems, results in changes in the state of these sensory systems. In some circumstances, we are able to use these state changes as transient records.

The remainder of the chapter describes the role of transient memories in the overall information processing, including their role in creating permanent memories. At one time it was thought that there was a sequence of memories, that information passed from sensory memory to short-term memory and then to long-term memory. The next section discusses the problems associated with the concept of an intermediate short-term memory. The remainder of the chapter describes the more current idea of a working memory.

Sensory systems can have transient records of the information they are processing, and these can serve as temporary memories.

The Rise and Fall of the Theory of Short-Term Memory

The Atkinson and Shiffrin theory of memory (see Figure 1.11 from Chapter 1) proposed that there are separate short-term and long-term memories and that information is temporarily held in short-term memory by rehearsal. Although it is in short-term memory, a permanent representation of the information can be built up in long-term memory. The classic example is a telephone number that we will repeat over and over again until it is memorized. The key feature of this theory is the proposal that short-term memory is a necessary halfway station between sensory memory and long-term memory. Many psychology texts still include this proposal of two separate memories, and it is worthwhile reviewing why this view was held. The distinction between short-term and long-term memory was predicated on a number of claims; particularly significant were the following three:

- Rehearsal of information in short-term memory builds up a representation of that information in long-term memory.
- The types of encodings are different in short-term and long-term memory.
- There is a dramatic difference in the duration of short-term and long-term memory.

Each of these claims was based on some empirical data. However, it has become apparent that all the data cannot be properly understood if there is assumed to be a short-term memory between sensory memory and long-term memory. This section considers each claim, the evidence for it, and the problems with it.

The theory of short-term memory was based on claims about the effects of rehearsal, coding differences, and retention of information.

Effects of Rehearsal

As discussed in Chapter 1, Rundus (1971) showed that the longer information is rehearsed, the better it is recalled. He asked subjects to rehearse out loud and counted the number of times they rehearsed each word. He found that the words that were rehearsed more often were better recalled (see Figure 1.12). This result was just as predicted by the Atkinson and Shiffrin theory, which proposed that information got into long-term memory by being rehearsed in short-term memory. Sometimes, however, rehearsal does little to improve long-term memory. Glenberg, Smith, and Green (1977) had subjects study a four-digit number for 2 sec, then rehearse a word for 2, 6, or 18 sec, and finally recall the four digits. Subjects participated in 64 trials. Subjects thought that the experimenter's interest was in digit recall and that the words were only being used to fill up the retention interval. After the experiment, subjects were asked to recall the words they had been rehearsing. Their recall averaged an abysmal 11, 7, and 12 percent, respectively, in the 2-, 6-, and 18-sec rehearsal intervals. Thus, subjects showed little recall and no relationship between the amount of rehearsal and the amount of recall. Glenberg et al. also tried a recognition test for the words and found only a weak effect of amount of rehearsal on memory performance.

Craik and Watkins (1973) used another paradigm to show the lack of an effect of passive rehearsal on memory. Their subjects heard a list of 21 words and were supposed to recall the last word that began with a certain letter. Thus, if the critical letter was G, subjects might hear *daughter, rifle, garden, grain, table, football, anchor, giraffe, fish, tooth, book, heart, mouse, gold, can, ball, paper, fire, glass, house, shoe,* and should recall *glass*. When the subjects heard the first G-word, they did not know whether it was the word they would have to recall; therefore, they had to rehearse it until they heard the next G-word. Different words had to be rehearsed for different lengths of time. In the example given, *garden* would be rehearsed for zero words, *grain* three words, *giraffe* five words, *gold* four words, and *glass* two words. After studying 27 such lists, subjects were given a surprise recall of all the words. Craik and Watkins found no relationship between how long the word was rehearsed and its final probability of recall.

Perhaps the most dramatic evidence for the lack of relationship between the amount of rehearsal and long-term recall is the report cited by Neisser (1982) of a Professor Sanford, who estimated that he had read the family prayers at meals some 5000 times over 25 years. Despite all this rehearsal, Professor Sanford found that when he tested his memory, he had very little memory for the prayers. Sheer rehearsal is not enough to guarantee good long-term memory.

If it is not sheer repetition, what does determine how much we remember? Rundus (refer to Figure 1.12) found a relationship between number of rehearsals and recall, but, unlike the experiments just cited, his subjects were actively processing the material with an eye to remembering it. In an influential article, Craik and Lockhart (1972) argued that what was critical was the depth to which information was processed. According to this theory, called the **depth of processing theory**, rehearsal improves memory only if the material is rehearsed in a deep and meaningful way; passive rehearsal does not result in better memory. This point of view was nicely illustrated in a series of experiments by Craik and Tulving (1975). In one experiment they showed subjects a word, such as *table*, and asked them to make three types of judgments. The shallow-level judgment, about case, was whether the word was in capitals. The intermediate-level judgment was whether it rhymed with another word, for example, *cable*. The deep-level judgment was whether it fit in a sentence, for example, "He put the plate on the ________." They later asked subjects to recognize the words. Figure 5.4 shows the proportion of words recognized as a function of the type of processing of the words. The more deeply processed words were better remembered. Similar effects of depth of processing can be shown in memory for faces. Subjects show better memory for photos of faces if they are asked to judge whether the person is honest rather than whether the person is male or female (Bloom & Mudd, 1991; Sporer, 1991).

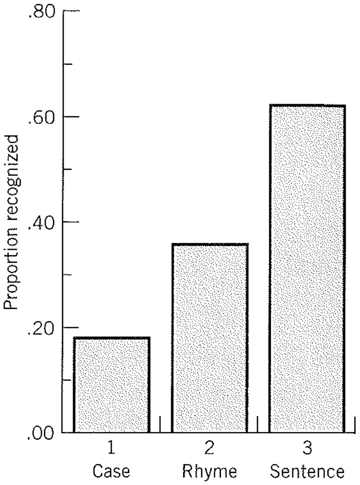

FIGURE 5.4 Proportion of words recognized as a function of type of initial processing. (From Craik & Tulving, 1975.)

Craik and Lockhart argued that memory for material improves with more time for rehearsal only if the rehearsal creates a deeper encoding of the material. There was no improvement with rehearsal time in the Glenberg et al. or the Craik and Watkins studies because subjects continued to rehearse the words at a shallow level. The depth of processing explanation has been criticized because the concept of depth is somewhat vague (Nelson, 1977) and because, as reviewed in Chapter 8, there are interactions between the type of processing at study and at test. However, depth of processing experiments such as that reviewed here remains significant in that they show that mere rehearsal of material does not automatically result in better memory. This result disconfirmed the original Atkinson and Shiffrin theory of short-term memory, which proposed that information was transferred to long-term memory as a function of verbal rehearsal.

Passive rehearsal of material will not increase its recall, but deeper processing does.

Coding Differences

One argument for a separate short-term memory was that information was coded differently in short-term memory and long-term memory. It seemed that the encodings in short-term memory were sensory in nature. People often rehearse material, such as word lists in experiments or telephone numbers in everyday life, by saying the items over and over again to themselves. This means that the information tends to have articulatory and acoustic features. It was thought that information in long-term memory was more concerned with representing the meaning of the items.

A classic experiment showing this distinction between short-term and long-term memory was performed by Kintsch and Buschke (1969). They had subjects study lists of 16 words presented visually at a rate of one word every 2 sec. They then provided subjects with one word from the list and asked them to recall the word that followed it in the list. It is worth reviewing how the Atkinson and Shiffrin theory is supposed to apply to memory for such a list of words (see the discussion surrounding Figure 1.12). The subject was assumed to be rehearsing in short-term memory the last few words read. Therefore, when asked to recall the words after study, the subject should display particularly good memory for the last few words in the list because these were rehearsed. This result did occur; the advantage for the last few words is referred to as the **recency effect**. Memory for the rest of the list depended on retrieving the words from long-term memory.

Kintsch and Bushke reasoned that if short-term memory was verbal in character, there would be a lot of acoustic interference if the words in the list sounded alike—for example, *see* and *sea*. If subjects were asked what followed *see*, they might recall the word that followed *sea*. Such acoustical confusion would be a particular problem for words at the end of the list, which were supposed to be in short-term memory. On the other hand, words from the beginning of the list might produce semantic confusion if they were synonyms, such as *sea* and *ocean*, because these words were in long-term memory, where the coding was supposed to be semantic.

In three conditions, subjects saw words that were unrelated, synonyms (similar meaning), or homophones (similar sounding). Kintsch and Bushke found that recall for the last few words in the list was impaired if the words were homophones and that memory for the first words of the list was impaired if the words were synonyms. It seemed that short-term memory was acoustic (sound-oriented) and long-term memory was semantic (meaning-oriented), as hypothesized.

Yet, serious problems arise when one tries to advance coding differences as a fundamental distinction between short-term memory and long-term memory. For instance, tasks that are supposed to rely on short-term memory also take advantage of meaningful codes. Bower and Springston (1970) showed that subjects had much larger memory spans for sequences of letters when they formed meaningful acronyms, as in,

IBM FBI ABC USA

Memory for these letters was supported by semantic information which, according to the short-term memory theory, is a long-term memory coding. In addition, the fact that people can remember rhymes and sounds for long periods of time provides evidence of acoustic codings in long-term memory.

People can also make semantic confusions in a short-term memory task. Potter and Lombardi (1990) presented subjects with sentences such as

The knight rounded the palace searching for a place to enter.

Subjects then heard a list that included the word *castle*. After hearing the list, they were asked to recall the original sentence. About a quarter of the subjects recalled

> The knight rounded the castle searching for a place to enter.

and thus intruded the semantically related word. This semantic confusion indicates that our immediate memory for a list of words (in this case a sentence) involves semantic information as well as acoustic information.

An alternative proposal, based on the concept of depth of processing (Craik & Lockhart, 1972; Wickelgren, 1974), proposes that different types of information are forgotten at different rates and that sensory information may be more shallowly processed and may be forgotten more rapidly. Initially, memories may show a preponderance of sensory traces, but as time passes, semantic traces remain. (This issue of differential forgetting for different types of memory is addressed in more detail in Chapter 6.) Thus, acoustic confusion predominates early in the Kintsch and Bushke experiment because the acoustic information has not been forgotten. As time passes the acoustic information is forgotten, leaving primarily semantic information, which was there all the time, and resulting in mainly semantic confusions.

Both acoustic and semantic information can serve as the basis of memory performance at short and long delays.

The Retention Function

The ability to recall information decays rapidly in the short interval after it has been studied. According to the hypothesis of a separate short-term memory, the superior memory for recent material indicates that it is held in a special short-term memory store and the rapid decay reflects loss from short-term memory. Several other paradigms have been used to show that there is an initial rapid loss of information. Brown (1958) and Peterson and Peterson (1959) traced the retention of simple nonsense trigrams, such as CHJ, over 18 sec. Subjects might not be expected to exhibit much forgetting of three letters over such a short period. However, the experimenters distracted subjects by having them count backwards by threes from a large number, such as 418. With this sort of distracting task there was rapid forgetting of the trigrams. Figure 5.5 shows the retention functions obtained. A retention function plots memory performance as a function of the delay until recall. Note that retention decreased to about 20 percent, not to zero, supposedly reflecting what the subjects were able to store in long-term memory. Given longer initial study, subjects would have shown a higher level of performance after 18 sec, reflecting the transfer of more information to long-term memory.

There are several problems with such demonstrations. Such steeply decreasing retention functions are not obtained for subjects' recall of their first

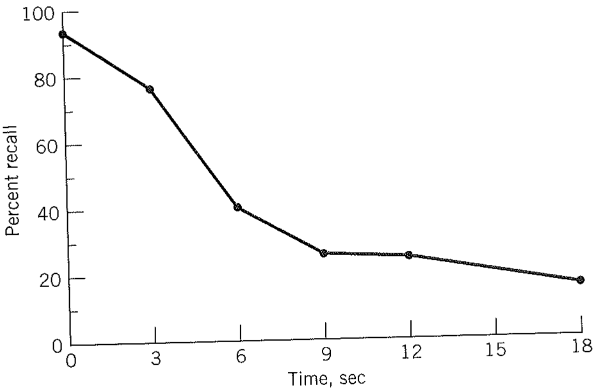

FIGURE 5.5 Decrease in recall as a function of duration of the distracting task. (From Murdock, 1961.)

nonsense trigram (Keppel & Underwood, 1962); in this case they show relatively little forgetting. Rapid forgetting occurs only after subjects have been in the experiment for many trials and have seen many trigrams. Thus, an important contribution to this forgetting is interference from earlier trigrams that have been studied and are stored in long-term memory. Chapter 7 examines these studies and retention effects at greater length, but for now it should be noted that the forgetting in Figure 5.5 does not simply reflect a short-term memory phenomenon, because it depends critically on what the subject has already committed to long-term memory.

The retention curve in Figure 5.5 appears to show rapid initial forgetting followed by no further forgetting. This apparent discontinuity of the forgetting curve was used to argue for two stores (e.g., Waugh & Norman, 1965). The initial rapid drop-off was supposed to be due to loss from short-term memory, whereas the flat portion of the curve was supposed to represent what got into long-term memory. However, note that performance is still dropping off from 9 to 18 sec (and this curve would continue to drop off beyond 18 sec). Wickelgren pointed out that all retention curves for any period of time show **negative acceleration**, meaning that the rate of loss is initially large but decreases with time. Consider the retention study of Ebbinghaus (Figure 1.1 from Chapter 1). He looked at retention of material that was much better learned than that represented in Figure 5.5 over intervals of up to 30 days. Figure 1.2 shows a negatively accelerated retention curve with an apparent discontinuity at around two days, where the curve is flattening. Clearly, there is not a short-term memory of two days! The forms of retention curves are not evidence for a discontinuity between short-term and long-term memory; the curves are really continuous, and their apparent discontinuity is merely an artifact of the scales on which they are graphed. Chapter 7 discusses the nature of these retention functions more fully.

The shape of the early part of the retention function and the factors that influence it are the same as for the later part of the retention function.

Conclusions about Short-Term Memory

The two-memory proposal claimed that there are two separate memory stores with their own distinct characteristics and that information passes from the short-term store to the long-term store. The alternative proposal is that there is just one general memory system into which information from our sensory systems is encoded (e.g., Melton, 1963; Wickelgren, 1974). Different memories in that system can have different attributes. The way we process that information can influence how well we remember it. In particular, more deeply processed information tends to be forgotten less rapidly. There is no discontinuity in the retention functions for any kind of material. All forgetting functions are negatively accelerated through any retention interval.

The data on the effects of rehearsal, types of codes, and retention effects can be accommodated without postulating a short-term memory as a halfway station between sensory memory and long-term memory. However, people do engage in rehearsal processes, and these processes can affect memory performance. Baddeley (e.g., 1986) proposed a concept of slave **rehearsal systems** to help explain these effects. These rehearsal systems are considered next.

Rehearsal Systems

A previous section reviewed the evidence for the existence of sensory memories that maintain transient records of our experience. For instance, we have an acoustic memory that holds information for a few seconds. What happens if we say a set of numbers to ourselves? Presumably, we are filling our echoic memory with a sensory record of our own speech. If we do this over and over again, we can keep a record of those digits in echoic memory. By rehearsal, we are making our echoic memory a system for holding the digits. There are other ways in which we can use our bodies as systems for holding information. We can remember a digit by holding out the appropriate number of fingers; we can remember where something is in space by staring at that location; we can remember the width of a board by placing our two hands at its sides and then keeping our hands that far apart. People can be extremely imaginative in how they use their bodies as transient memories to hold information. The verbal system is particularly important, and a great deal of research has been devoted to how this system may be used to hold information. Baddeley used the term **phonological loop** to refer to our use of the verbal system as a transient memory.

The Phonological Loop

According to Baddeley, the phonological loop is composed of two systems—a store capable of holding speech-based information and a system capable of subvocal speech (speaking to oneself). The phonological loop does not require speaking aloud. Since no auditory signal is needed, the phonological loop is not quite the same thing as the echoic store. Baddeley and Lewis (1981) referred to the system that holds speech-based information as the **inner ear** and the system for speaking to oneself as the **inner voice**. Although they are not the same, the inner ear and the inner voice are closely tied to the outer ear and the outer voice. Baddeley proposed that the phonological loop is capable of holding about 2 sec worth of information. Some of the best evidence for such a loop involves **memory-span tests** for various kinds of information that people tend to rehearse verbally. In a memory-span test, the subjects hear a series of words and try to repeat them back perfectly. Baddeley, Thomson, and Buchanan (1975) had subjects try to repeat five words. They varied the number of syllables in the words from one syllable,

> wit, sum, harm, bag, top

to five syllables,

> university, opportunity, expository, participation, auditorium

Figure 5.6 shows the recall results. Recall decreased as the number of syllables increased, falling from about 4.5 words for the one-syllable words to 2.6 words for the five-syllable words. Figure 5.6 also plots the reading rate—the number of words of each syllable length that can be said in 1 sec. The reading rate also decreased as number of syllables increased. Dividing the number recalled by the reading rate produces a value of about 2 for all syllable lengths. For instance,

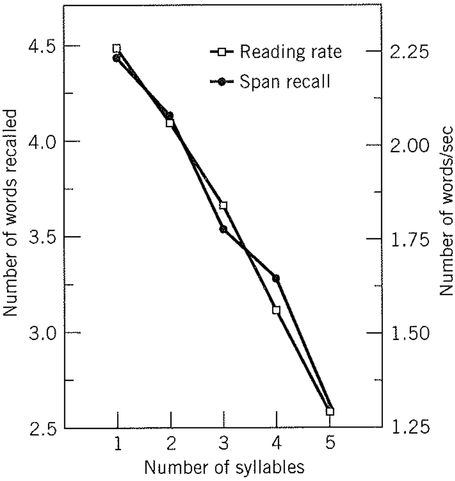

FIGURE 5.6 Number of words recalled (left-hand scale) and mean reading rate (right-hand scale) for sequences of five words as a function of the number of syllables in the words. (From Baddeley, 1986.)

subjects could recall about 3.5 of 5 three-syllable words and their reading rate was about 1.8 words/sec—giving 3.5/1.8, or approximately 2-sec worth of words. This result implies that subjects can recall what they can rehearse in 2 sec. The capacity of the phonological loop is limited by how far back the inner ear can remember hearing a word. The research of Darwin, Turvey, and Crowder (1972) and Glucksberg and Cowan (1970), reviewed earlier, indicated that echoic memory had a span of 4 or 5 sec. This span is a good bit longer than that estimated for Baddeley's phonological loop, but these studies involved rather different procedures and measures.

The crucial variable is spoken duration, not number of syllables. Words with long vowels, such as *Friday* and *harpoon,* show shorter spans than words with short vowels, such as *wicked* and *bishop* (Baddeley, 1997). There is an interesting relationship between speech rate and digit span. **Digit span** is a fairly standard test of memory that appears in intelligence tests. It involves seeing how many single-digit numbers a person can repeat back perfectly. Adult speakers of English have spans of about seven or eight digits. There is a correlation across languages between span and articulation length for digits. The articulation rate for Chinese is 265 msec/digit (Hoosain & Salili, 1988), compared with 321 msec/digit for English and 385 msec/digit for Welsh (Ellis & Hennelly, 1980). Correspondingly, spans are longest for Chinese (9.9), intermediate for English (6.6), and shortest for Welsh (5.8).

Trying to maintain information in the phonological loop is analogous to the circus act that involves spinning plates on reeds. The circus performer starts one plate spinning on a reed, then another on another reed, then another, and so on. The performer must return to the first before it slows down and falls off, respin it, and then respin the rest of the plates. There are only so many plates that the performer can keep spinning. Baddeley proposed the same situation with respect to working memory. If we try to keep too many items in working memory, by the time we get back to rehearse the first one, its representation is no longer available in the phonological store.

This phonological loop seems to involve speech. Conrad (1964) performed some of the original research establishing this point. He showed that when subjects misremembered something from a memory-span task, they tended to recall something that sounded similar. In his experiment, subjects were asked to recall a string of letters, such as HBKLMW. They were much more likely to misrecall B as its soundalike V than as an S, which does not sound similar. Conrad also found that subjects had a harder time recalling a string of letters that contained a high proportion of rhyming letters (such as BCTHVZ) than a string that did not (such as HBKLMW). He speculated that this problem arose because of confusion among the similar-sounding letters.

Further evidence that the phonological loop involves speech is provided by articulatory suppression techniques, which require the subject to say repeatedly an irrelevant word, such as *the* (Baddeley, Lewis, & Vallar, 1984). Subjects repeat the word while they listen to a list of words and while they try to write down the list in recall. Requiring the subject to say the word prevents the rehearsing of anything else in the phonological loop. When subjects are required to engage in such articulatory suppression, their memory spans are shorter. In contrast, concurrent nonspeech tasks, such as tapping, do not affect span. Articulatory suppression also reduces the phonological confusions among letters that Conrad found. When the original list is presented visually and the subject is engaged in articulatory suppression, the effect of phonological similarity is eliminated; it is reduced, but not eliminated, when the original presentation is auditory. With auditory presentation, the subject still has a phonological encoding of the original presentation, which can be confused on a phonological basis (Baddeley et al., 1984); with visual presentation, the subjects have neither the auditory presentation nor the results of their inner speech.

What is the difference between Baddeley's phonological loop and the short-term memory of Atkinson and Shiffrin? Although both are transient and rehearse verbal information, the phonological loop is not a halfway station to long-term memory. Information does not have to go through the loop to get into permanent memory, and while it is being rehearsed, no buildup of its permanent representation need occur. There is as little relationship between the phonological loop and what happens to permanent memory as there is between notes we take on a sheet of paper and things we store in our permanent memory. Like the paper, the phonological loop can be a valuable system for storing information; unlike the paper, however, it is a transient representation, and all records can be lost if rehearsal ceases.

The phonological loop can maintain about 2 seconds of speech by implicit verbal rehearsal.

The Visuo-spatial Sketch Pad

Among the other slave rehearsal systems proposed by Baddeley is the **visuo-spatial sketch pad**, a system for rehearsing visual or spatial information. He proposed that people can rehearse material by creating mental images that are in some ways like the sensory experiences they have when seeing. For instance, Baddeley (an Englishman) reported that he had difficulty following an American football game on the radio while driving. He had developed a complex image of the game, which was interfering with his ability to process the visual information required for driving. His imagery process was interfering with his visual process, suggesting that they are part of the same system.

Figure 5.7 illustrates some material that Baddeley adapted from Brooks (1967) to study the use of the visuo-spatial sketch pad to store visual information. In the spatial condition, subjects heard a series of sentences that they were to remember. To help them remember the sentences, they were instructed to imagine placing the objects in a 4 × 4 matrix. Figure 5.7 illustrates how the matrix could code the information in the spatial sentences. In the nonsense condition, they heard sentences that were similar but could not be coded in a matrix. Subjects were able to remember about eight of the spatial sentences and

		3	4
	1	2	5
		7	6
		8	

Spatial material	Nonsense material
In the starting square put a 1.	In the starting square put a 1.
In the next square to the *right* put a 2.	In the next square to the *quick* put a 2.
In the next square *up* put a 3.	In the next square to the *good* put a 3.
In the next square to the *right* put a 4.	In the next square to the *quick* put a 4.
In the next square *down* put a 5.	In the next square to the *bad* put a 5.
In the next square *down* put a 6.	In the next square to the *bad* put a 6.
In the next square to the *left* put a 7.	In the next square to the *slow* put a 7.
In the next square *down* put an 8.	In the next square to the *bad* put an 8.

FIGURE 5.7 Example of material used by Baddeley in his study of the visuo-spatial sketch pad. *Source:* From A. D. Baddeley, S. Grant, E. Wight, and N. Thomson. *Attention and Performance V*, Volume 5. Imagery and Visual Working Memory. Copyright © 1975 by Academic Press. Reprinted by permission.

only five of the nonsense sentences; this suggests that they were able to use the image of the 4 × 4 matrix to supplement their memory for the sentences.

In an important elaboration on this basic study, Baddeley, Grant, Wight, and Thomson (1975) looked at the effect of a concurrent spatial tracking task on memory for the sentences. The concurrent tracking task involved keeping a stylus in contact with a spot of light that followed a circular track. Subjects had to remember eight spatial sentences or five nonsense sentences like those in Figure 5.7. Figure 5.8 shows the total number of errors made in remembering these sentences when the subjects were and were not simultaneously perform-

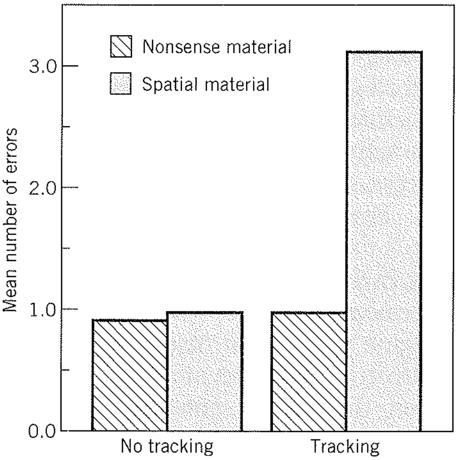

FIGURE 5.8 The influence of concurrent tracking on memory span for spatial and nonspatial sequences. (From Baddeley et al., 1975.)

ing a spatial tracking task. The error rate was approximately the same for spatial and nonsense material without a spatial tracking task and was not impaired for nonsense sentences given a spatial tracking task. The error rate rose dramatically when subjects had to perform a spatial tracking task concurrently with memorizing the spatial sentences. This result indicates that the visuo-spatial sketch pad that supports the memory of the spatial sentences is tapping the same system that supports the representation of the tracking task.

The visuo-spatial sketch pad can maintain transient information in a spatial organization.

Working Memory and the Central Executive

Figure 5.9 illustrates Baddeley's overall conception of how these various slave systems interact. A central executive controls the use of various slave systems, like the visuo-spatial sketch pad and the phonological loop. The **central executive** can put information into any of these slave systems or retrieve information from the systems. It can also translate information from one system to the other. Baddeley claimed that the central executive needs its own transient store of information to make decisions about how to control the slave systems.

Baddeley calls the overall system displayed in Figure 5.9 **working memory**. By this he means to denote that it is the system that is holding all the information that is currently being operated upon. Baddeley believes that the capacity of all these systems, particularly the central executive, is critical to mental performance. The different memories in Figure 5.9 are independent. Thus, if one is using the articulatory loop to rehearse a set of words, it will have little effect on the performance of a more cognitive task that requires use of the central executive or spatial sketchpad.

Consider the involvement of these systems in performing a mental multiplication task, such as 37 × 28. Try to figure out this product in your head and

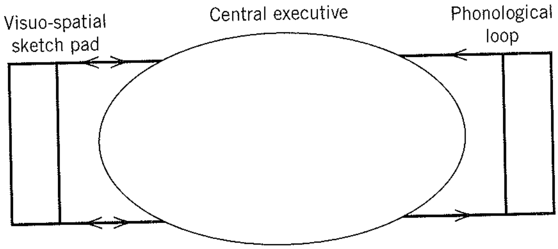

FIGURE 5.9 Baddeley's theory of working memory where a central executive coordinates a set of slave systems. *Source:* From A. D. Baddeley. *Working memory: Oxford psychology series* No. 11. Copyright © 1986. Reprinted by permission of Oxford University Press.

observe what you do. You might try to hold an image of the multiplication, which looks like

$$\begin{array}{r} 37 \\ \times\,28 \\ \hline 296 \\ 740 \\ \hline 1036 \end{array}$$

You might verbally rehearse information to help you retain it. Thus, you might well use both your phonological loop and your visuo-spatial sketch pad to help you perform the task. But you need to access information that is in neither store. You have to remember that your task is multiplication; where you are in the multiplication; and temporary carries, such as 5 from 56. All this information is held by the central executive and is used to determine the course of solving the problem and the use of the slave systems. In addition, you would have to remember information such as 7 × 8 = 56 from permanent memory. Another function of the central executive is to coordinate all of these memories.

In Baddeley's theory the central executive and the slave rehearsal systems constitute working memory.

The Sternberg Paradigm

Just because someone is rehearsing information in working memory does not mean that they have instantaneous access to the information. Sternberg (1969) introduced a paradigm that became popular for studying speed of access to such information. His paradigm is now referred to as the **Sternberg paradigm**. He gave subjects a set of digits to hold in memory, such as 4 1 8 5, and then he asked them whether a particular probe digit was in the set. For this example a positive probe digit would be 8, and a negative probe would be 6. Sternberg was interested in the speed with which his subjects could make the judgment as a function of the size of the set they were holding in memory. Figure 5.10 shows his results. The straight line is the best-fitting linear function relating judgment time to the size of the memory set. As the size of the memory set got larger, subjects took longer to make the judgment in the case of both positive probes and negative probes. He found that each digit added an extra 38 msec to the judgment time. This 38 msec is the slope of the linear function in Figure 5.10.

Sternberg proposed an influential theory to account for these results: Subjects serially searched through the list of digits they held in memory. If they found the digit in the list, they responded *yes* to the probe; otherwise, they responded *no*. The more digits in the list, the longer it took to search the list. The 38 msec measured the time to consider one item in the list. The positive probe might be expected to result in a shallower slope, because the subject could stop as soon as the target digit was encountered, whereas in the case of a negative

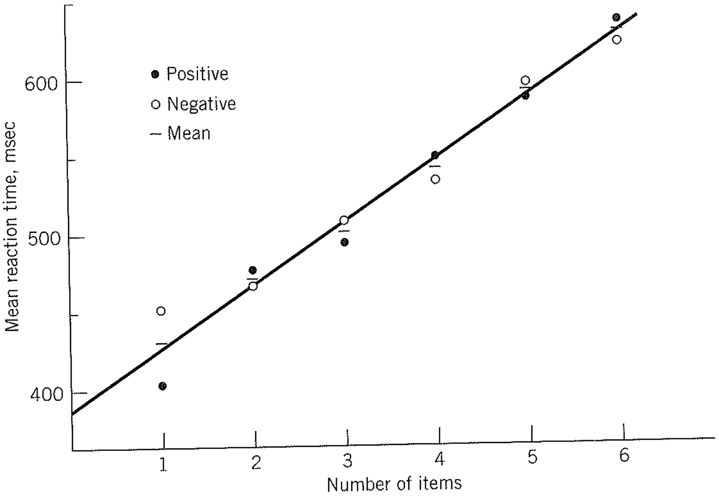

FIGURE 5.10 Judgment time as a function of number of items in a memory set. (From Sternberg, 1969.) *Source:* From J. Antrobus. *Cognition and affect.* Copyright © 1970. Published by Little, Brown and Company. Reprinted by permission.

probe the subject would have to exhaust the list. However, Sternberg proposed that, even in the case of a positive probe, subjects exhausted the list before responding. He argued that the scanning was taking place very rapidly and that checking whether to stop (because the probe had been found) would take longer than just going on to the end. Subjects certainly are not aware of doing any of this scanning; it is all happening too fast.

Many studies have involved variations of Sternberg's paradigm, and many alternative theories have been advanced for his data (see Glass, 1984, for one review). The functions are frequently not as linear as reported by Sternberg and have a decided curvilinear trend such that the rate of increase slows down for high memory set sizes. Even Sternberg's data contain a hint of this trend, since the increase for positive probes is largest in going from memory set sizes of one to two.

Some researchers (e.g., James Anderson, 1973) have argued that 38 msec is too rapid a comparison process to implement neurally. They have therefore advocated a parallel comparison process in which all the digits in the memory set are compared simultaneously against the probe. A single neural firing takes about 10 msec (see review in Chapter 1); thus, there can be a sequence of only about four neurons involved in checking an element for a match, which some people consider too few to perform a comparison. Parallel processing models have been proposed (e.g., Jones & Anderson, 1987) in which all the items in the memory set are processed at once, but the time to process the items is a function of how active they are. These models assume that there is a limit on how much activation can be allocated to the items. The more elements there are in this memory set, the less active any one item is, and the slower it will be processed.

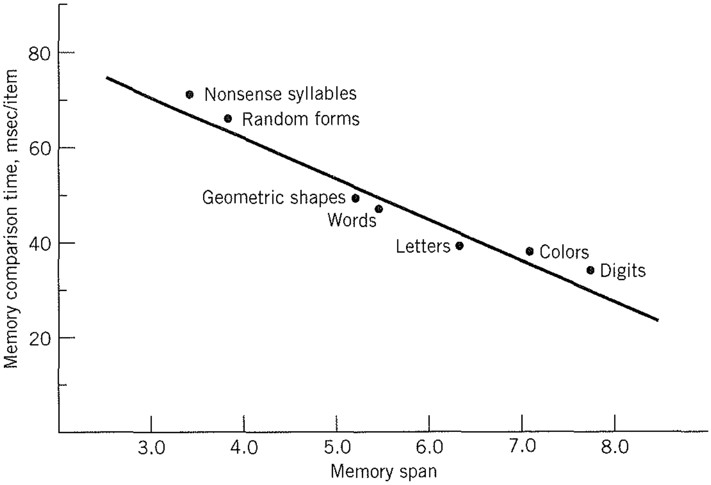

FIGURE 5.11 Memory comparison rate and memory span covary. (From Cavanagh, 1972). *Source:* From J. P. Cavanagh. Relation between the immediate memory span and the memory search rate. *Psychological Review*, Volume 79. Copyright © 1972 by the American Psychological Association. Reprinted by permission.

In terms of Baddeley's theory, the digits are presumably being held in the phonological loop. Thus, Sternberg's results are apparently related to the rehearsal process. Cavanagh (1972) looked at the relationship between memory span (the maximum number of elements that can be recalled perfectly) for various types of materials and the slope in a Sternberg task (e.g., the 38-msec increase shown in Figure 5.10). Figure 5.11 displays his results. Some of the material is verbal (nonsense syllables, words, letters, digits) and presumably is rehearsed in the phonological loop, whereas other information is visual (random forms, geometric shapes, colors) and presumably is rehearsed in the visuospatial sketch pad. The abscissa (memory span) in Figure 5.11 reveals a wide variation in how many items can be held in a span, and the ordinate (memory comparison time) reveals a wide variation in slope in a Sternberg task. The straight-line function in Figure 5.12 reveals that the two are closely related such that shorter spans are associated with larger slopes.

One explanation of the results of Cavanagh goes as follows: As Baddeley argued (see the discussion relating to Figure 5.6), memory span for these items varies because they vary in the speed at which they can be rehearsed. Compare digits (memory span of eight) and words (memory span of five) and assume a phonological loop of 2.0 sec. The digits would be rehearsed at the rate of 2.0 ÷ 8 = 0.25 sec/digit, and the words would be rehearsed at the rate of 2.0 ÷ 5 = 0.40 sec/word. Suppose that the subject was trying to hold a four-item memory set in memory. In the case of digits, the subject would be able to rehearse the digits every 0.25 × 4 = 1 sec, but the words would be rehearsed every 0.40 × 4 = 1.6 sec. On average, the digits would have been rehearsed more recently and would be more active. If time to access these items is a function of how active they are in the rehearsal system, Cavanagh's function would be expected, because slower rehearsal would result in less active elements and in shorter memory spans.

As subjects have to hold more items in a rehearsal system, their rate of access to any item decreases.

Rehearsal Processes in Lower Organisms

Humans apparently are not the only organisms that use rehearsal processes to maintain information. Considerable research has been performed studying rehearsal processes in pigeons in what is called **delayed match-to-sample task** (e.g., Grant, 1981; Honig, 1981; Maki, 1984). The typical trial might begin with a key lit red. After it has been lit for a period of time, say, 5 sec, the key is turned off, and the pigeon must wait for a period of time. After this retention interval, two keys are turned on—one red and one green. The pigeon must peck the key with the same color as the earlier lit key in order to obtain reinforcement. The initial key that the pigeon must match (the sample) varies from trial to trial. Pigeons are quite capable of solving this problem, but their accuracy in matching depends on the interval between the sample color and the test. Figure 5.12 presents some data from Grant (1976), showing how the probability of pecking the correct color falls off with delay. At all points, performance is quite a bit better than chance performance, which would be 50 percent.

This retention curve is like the retention curves displayed by humans (e.g., Figure 5.5). Humans try to bridge these intervals by rehearsing the material to

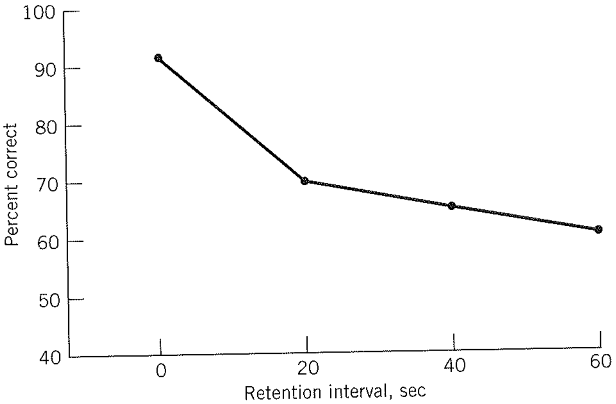

FIGURE 5.12 The percentage of correct choices (which key to peck) made by pigeons as a function of delay between the presentation of the information and opportunity to respond. *Source:* From D. S. Grant. *Learning and Motivation.* Volume 7. Copyright © 1976 by Academic Press. Reprinted by permission.

keep it active in working memory. There is evidence that pigeons also engage in rehearsal during this interval. For instance, humans show more rapid forgetting when they are distracted from rehearsal, and pigeons appear to do the same. Pigeons show better retention when the factors that might distract them from rehearsing are reduced, such as when the lights are turned off during the retention interval (e.g., Grant & Roberts, 1976; Roberts & Grant, 1978). With the lights out, the pigeons can no longer look around the experimental chamber and process distracting stimuli.

One mechanism that pigeons use to rehearse this information is body position; they remain oriented toward the critical key during the interval. This is a particularly clear case of how an organism can use its body as a transient memory for information. Postural rehearsal is not the only way in which pigeons can perform this task, however; they can also perform the task when the position of the colored key shifts from study to test and they must remember the color and not the location.

It further appears that pigeons can be "instructed" whether or not to rehearse the material (Maki & Hegvik, 1980). This phenomenon was demonstrated in experiments that were identical to match-to-sample experiments except that on some trials the pigeons did not get the opportunity to peck the key after the delay. They were given a cue to tell them whether or not they could peck. That is, after the pigeons had seen the original sample, a signal told them whether this was a trial in which they could peck or not peck. These cues are called remember cues and forget cues. For some pigeons, turning the house light on served as the remember cue, and its absence as the forget cue; for others, the cues were reversed. The pigeons remembered which key to peck quite well after a remember cue. Occasionally, they were given a surprise test after a forget cue; on such surprise trials, they were observed to show rapid forgetting.

These results are illustrated in Figure 5.13, which shows some data from Maki and Hegvik (1980). The percentage of recall in a delayed match-to-sample experiment is plotted for forget cues and remember cues at short delays (2 sec) and long delays (7 sec). Right after seeing the sample there was relatively little difference in performance with forget and remember cues. However, without the motivation to rehearse, the ability to remember where to peck dropped off dramatically over the 7-sec retention interval (forget cue). Apparently, the pigeons' ability to remember what to do was maintained by an active rehearsal process over the interval and they engaged in this rehearsal process only if they expected to be tested.

There is also evidence for a role for rehearsal in classical conditioning. Wagner's (1981) SOP theory of conditioning (mentioned in Chapter 2) claims that immediately after a conditioning event the organism is actively rehearsing the CS–US pairing and that the success of conditioning depends on this rehearsal successfully taking place. Evidence for this assertion was demonstrated in an experiment by Wagner, Rudy, and Whitlow (1973) on eyelid conditioning in rabbits. They followed a pairing of a CS and a puff of air by a surprising event (an unexpected pairing of two other stimuli). They predicted that this would cause the rabbit to cease rehearsing the CS–US pairing and start rehears-

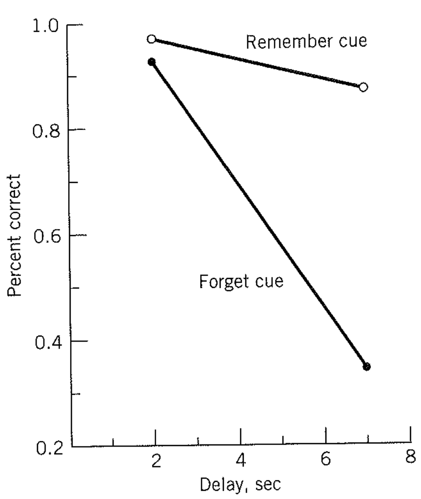

FIGURE 5.13 Retention in a delayed match-to-sample experiment as a function of whether the pigeon anticipated being tested or not. (From Maki & Hegvik, 1980.)

ing the new event. Figure 5.14 displays the degree of conditioning as a function of the interval between the CS–US pairing and the surprising event. The longer the interval before the surprising event, the more time the rabbits should have to rehearse the CS–US pairing. As shown, conditioning did increase as the rabbits had longer to rehearse the pairing.

Wagner (1978) also suggested that such rehearsal processes might be part of the explanation of latent inhibition, which causes difficulty for the

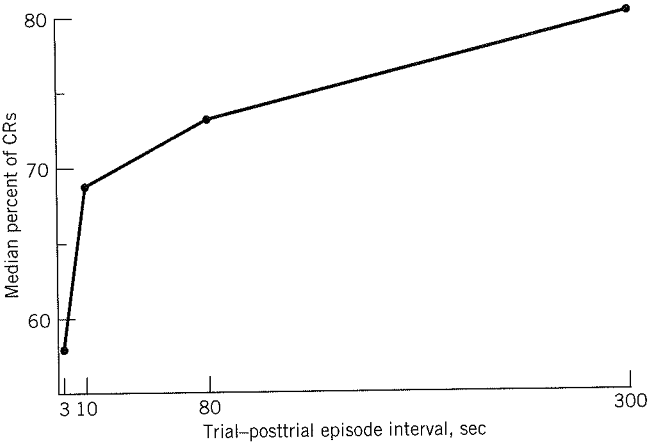

FIGURE 5.14 Amount of conditioning in four different groups of rabbits as a function of the interval between the conditioning trial and a surprising event. *Source:* From A. R. Wagner et al. Rehearsal in animal conditioning. *Journal of Experimental Psychology.* Volume 15. Copyright © 1989 by the American Psychological Association. Reprinted by permission.

Rescorla–Wagner theory. This is the phenomenon that preexposure to a CS without a US makes it more difficult to later condition the CS to the US. Wagner suggested that the preexposure might make the CS so expected that the animal does not encode the CS when the animal is presented with a US. If it is not encoded it cannot be rehearsed, and if it is not rehearsed it cannot be conditioned.

It appears that lower organisms rehearse stimuli to help them bridge retention intervals and to form associations.

The Neural Basis of Working Memory

The fact that nonhuman organisms engage in rehearsal processes has enabled considerable progress to be made in understanding the neural bases of working memory. The evidence shows that the frontal cortex plays a major role in working memory, at least in primates. The frontal cortex shows a major enlargement from lower mammals, such as the rat, to the monkey, and it shows a proportionately greater development from the monkey to the human. The frontal cortex plays an important role in tasks that can be considered working memory tasks. The task that has been most studied in this respect is a version of the **delayed-match-to-sample task** used with primates, which is illustrated in Figure 5.15. A monkey is shown an item of food, which is placed in one of two identical wells (Figure 5.15*a*). Then the wells are covered, and the monkey is prevented from looking at the scene for a delay period, typically 10 sec (Figure 5.15*b*). Finally, the monkey is given an opportunity to retrieve the food and must remember in which well it was hidden (Figure 5.15*c*). Monkeys with lesions to the frontal cortex are unable to perform this task (Jacobsen, 1935, 1936). Human infants are unable to perform successfully in similar tasks until their frontal cortices have matured at about one year of age (Diamond, 1991).

A particular small region of the frontal cortex is involved when the monkey must remember where in space the object was placed (Goldman-Rakic, 1988). This area, called area 46, is found on the side of the frontal cortex (see Figure 5.16). Lesions to this specific area produce deficits in this task. It has been shown that neurons in this region fire only during the delay period of the task, as if they are keeping information active during that interval. They are inactive before and after the delay. Moreover, different neurons in that region seem tuned to remembering objects in different portions of the visual field (Funahashi, Bruce, & Goldman-Rakic, 1991).

Goldman-Rakic (1992) examined monkey performance on other tasks that required maintaining different types of information over the delay interval. For instance, in one task the monkey had to remember to select a red circle and not a green square after an interval. A different region of the prefrontal cortex appeared to be involved in this task. Different neurons in this area fired when the red circle was being remembered rather than the green square. Goldman-

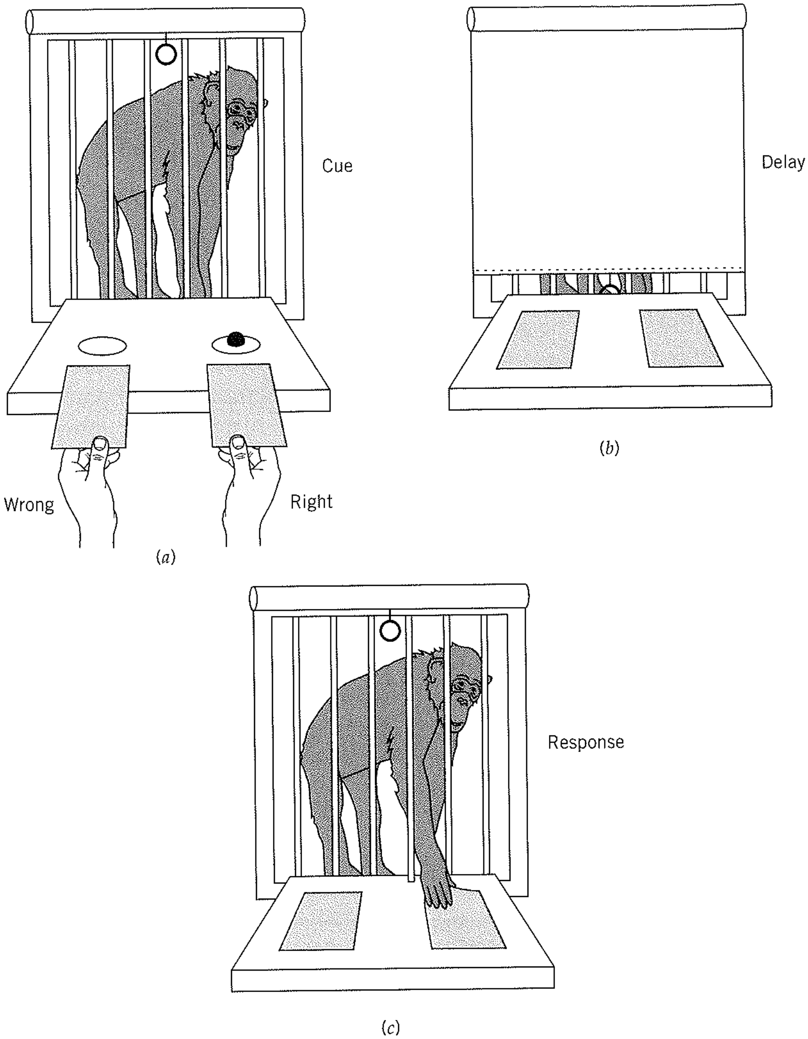

FIGURE 5.15 An example of a delayed memory task. (*a*) Food is placed in well on the right and covered; (*b*) curtain is drawn for delay period; and (*c*) curtain is lifted and monkey can lift cover from one of the wells. *Source:* From P. S. Goldman-Rakic. *Child Development*, Volume 58. Development of cortical circuitry and cognitive function. Copyright © 1987 by the Society for Research in Child Development. Reprinted by permission.

Rakic speculated that the prefrontal cortex is parceled into many small regions, each responsible for remembering a different kind of information.

The prefrontal cortex has strong connections with the hippocampus, a subcortical structure that has a major role in learning (see Chapters 3 and 8). The different regions of the cortex have appropriate connections to the other more

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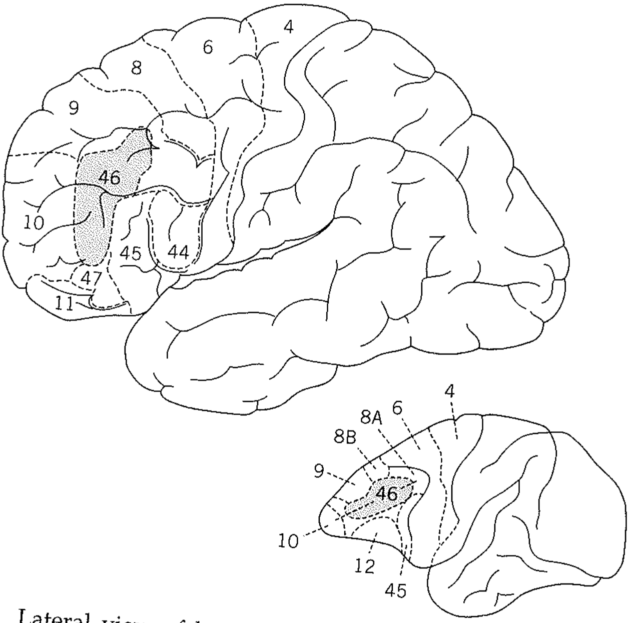

FIGURE 5.16 Lateral view of human and monkey cerebral cortex, with area 46 shaded. *Source:* From P. S. Goldman-Rakic. *Handbook of physiology: the nervous system, higher functions of the brain.* Copyright © 1987 by the American Physiological Society. Reprinted by permission.

sensory parts of the cortex. For instance, area 46, which serves as spatial working memory, has connections to the region of the parietal cortex that is responsible for processing spatial information in the world.

> *In primates, different small regions of the frontal cortex serve as working memory for different types of information.*

Neural Imaging of Working Memory in Humans

It appears that the prefrontal cortex serves similar working memory roles in humans as it does for other primates. Although it is not clear that the exact same regions of prefrontal cortex serve the exact same functions in humans, it does seem that different areas of the prefrontal cortex serve to maintain different kinds of information. Research with humans does not use lesion studies or single-cell recordings but rather various neural imaging techniques that track blood flow. Two of these imaging techniques are **positron emission tomography (PET)** and **functional magnetic resonance imaging (fMRI)**. Both techniques count on the fact that there is greater metabolic activity in regions of the brain that are more active. PET measures a radioactive tracer that will be concentrated in regions of the brain with greater blood flow. fMRI measures the different magnetic field caused by the fact that there is greater oxygen-rich blood (which has greater magnetic properties because of the iron in blood) in regions of greater activity.

Smith and Jonides (1995) used PET to compare the working memory required for spatial memory and object memory. Figure 5.17*a* illustrates the design they used to test spatial memory. In the memory condition, subjects saw a set of three dots that they had to remember for 3 seconds. Then a circle appeared, and they had to press a key once or twice to indicate whether the circle included the dot. This was contrasted with a control "perception" condition illustrated in Figure 5.17*b*. In this condition, subjects saw the dots and circle together and simply had to indicate whether the circle included the dot. Thus, they did not have to remember the spatial location of the dots. Smith and Jonides were interested in the differential activation produced by these two tasks. They found that the memory condition produced greater activation in the

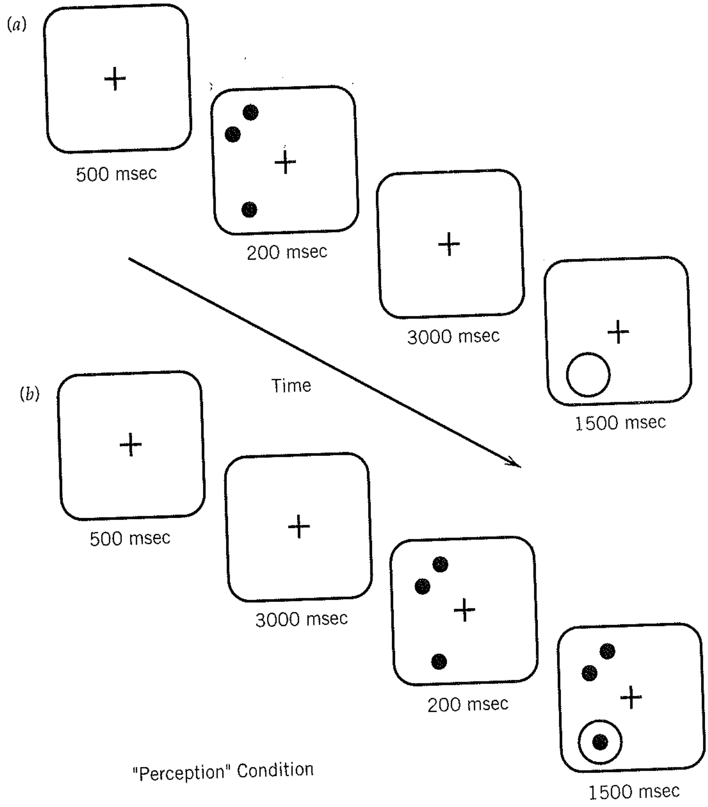

FIGURE 5.17 Schematic drawings of the events on each trial of the spatial memory and spatial perception conditions. *Source:* E. Smith and J. Jonides, *The Cognitive Neurosciences*, MIT Press. Copyright © 1995. Reprinted by permission.

right prefrontal cortex in a region close to area 46 (actually area 47—consult the human brain in Figure 5.16). Humans differ from other primates in that their brains are strongly lateralized, with the right hemisphere more involved in spatial and perceptual processing and the left hemisphere involved in more linguistic and symbolic tasks. Thus, it is not surprising that Smith and Jonides found activation concentration in the right frontal cortex.

Figure 5.18 illustrates the procedure Smith and Jonides used in the object memory task. In part (*a*), the experimental memory condition subjects saw two objects on either side of a cross. After a delay of 3 seconds, they saw one of these objects and had to press a key once or twice to indicate the object was identical to one of the original objects. In the "perception" control condition, they were shown three objects and had to press once or twice to indicate whether the central object matched either of the two peripheral objects. In a contrast between the memory condition and the control condition, Smith and Jonides found that the memory condition produced more prefrontal activation in the left hemisphere in area 6 (again consult the human brain in Figure 5.16). This is a region of the pre-

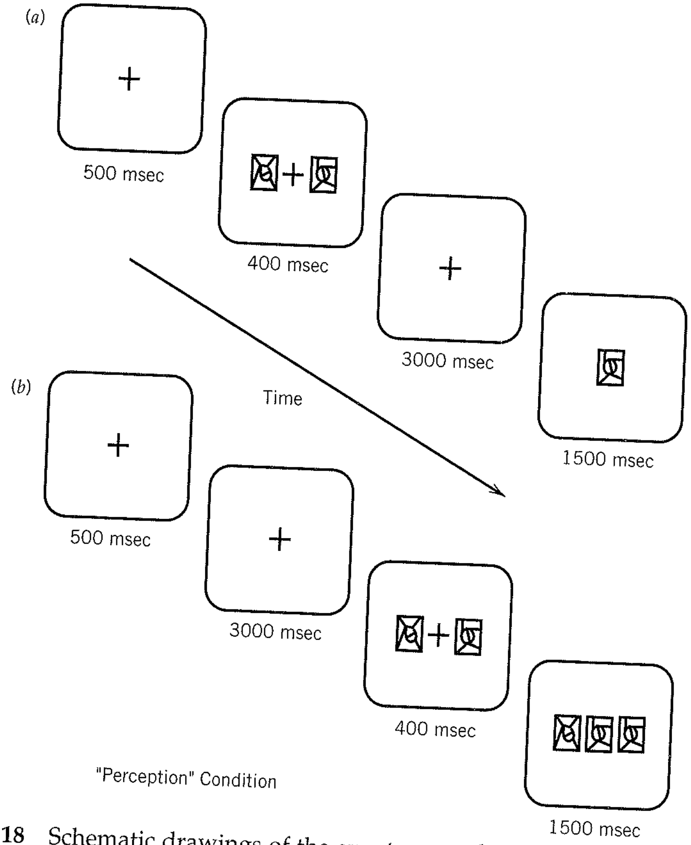

FIGURE 5.18 Schematic drawings of the events on each trial of the object memory and object perception conditions. *Source:* E. Smith and J. Jonides, *The Cognitive Neurosciences*, MIT Press. Copyright © 1995. Reprinted by permission.

frontal cortex in a region that has been associated with linguistic processing (Petrides, Alivisatos, Evans, & Meyer, 1993). Smith and Jonides suggest that their subjects may have been verbally labeling the shapes to help remember them.

When humans maintain information over delays, they show activation in different prefrontal areas for different types of material.

Final Reflections

This chapter has described some of the systems that hold temporary information. It is remarkable how many there are. Sensory systems briefly hold the information they are receiving so that the organism has a chance to encode it into a permanent memory. Information can also be maintained in various sensory-like buffers by slave rehearsal processes. The information in these various transient memories is used to guide our information processing. For this reason they can be collectively referred to as working memory.

It might seem a bit peculiar to speak of lower organisms, such as pigeons and rabbits, as having expectations and engaging in active rehearsal processes. However, it is to the advantage of lower organisms as well as humans to keep certain information available even when it is no longer present in the environment. Although nonverbal organisms do not have phonological loops for rehearsal, which often seem the preferred means of rehearsal for humans, they probably do have other rehearsal systems for maintaining information in an active state when it is no longer present in the environment. For instance, pigeons orient to the key they will have to peck and maintain that orientation over a delay. In this case, they are using their body posture as a slave system to rehearse the information they have to remember. Although these animals are rehearsing information, as do humans, this similarity to human behavior does not imply that they are acting in the same conscious ways in which humans can act.

In all of these working memory tasks, there is some change in neural activation that encodes the information. The location of this neural activation can vary from the peripheral sensory systems to the prefrontal cortex. In all cases, however, when the activation returns to its base level the memory is lost. Therefore, we called this chapter a study of transient memory. However, patterns of activation can also produce changes in synaptic efficacy which will result in relatively permanent memories. The next three chapters are concerned with these relatively permanent memories.

Organisms can maintain information in transient memories to guide their information processing.

Further Readings

Crowder (1976) is a classic text surveying memory. Baddeley's textbook (1997) on human memory provides a good exposition of his theory of working memory, and his research monograph (1986) also presents his theory. Journals devoted to human memory include the *Journal of Language and Memory* (formerly the *Journal of Verbal Learning and Verbal Behavior*), *Memory and Cognition*, and the *Journal of Experimental Psychology: Learning, Memory and Cognition*. The *Scientific American* article by Goldman-Rakic (1992) discusses the role of the prefrontal cortex in the working memory of primates. Roitblat, Bever, and Terrace (1984) review research on animal memory and cognition.